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Behavior of cellular beams with sinusoidal openings

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Abstract

Experimental tests were conducted on full scale cellular beams with sinusoidal openings. The analysis of the experimental results showed two failure modes by the formation of four plastic hinges at the opening corners or by the local instability in the sinusoidal part of the opening. The second failure mode is new and is not covered by the codes as it is directly linked to an innovative shape of beam firstly developed by ArcelorMittal for the AngelinaTM beam. In order to assess the resistance of sinusoidal opening, it has been chosen to test isolated parts around the opening. An experimental program is performed with different quarters of sinusoidal openings to observe the failure modes and to provide results to be used in the validation of the finite element model developed in the study. Then, a parametrical study is made, based on the numerical results, in order to develop a new analytical model based on the same hypotheses as those available for castellated beams.

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Keywords: Experimental tests, cellular beams, sinusoidal openings, plastic hinges, local instability, numerical model, analytical model.

1. Introduction

Long span beams commonly used in steel construction started to use large web openings during the last century in order to reduce the floors depth by passing all services through the web heights. The presence of the large openings changes the local transfer of the internal forces, mainly the shear force. Several experimental studies have been led on cellular beams in order to better understand the complex behavior of those beams. First experimental studies on castellated beams are presented in 1957 [1] which pointed out the specific failure mode of the beams with openings in the web, which is known as the Vierendeel bending (fig.1). Redwood is one of the main scientists that worked on this specific failure mode and developed simple analytical approaches to design cellular beams [2]. Nowadays the common way to check an opening resistance is to separate the

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global internal loads (M_{Ed} , V_{Ed}) of the beam in local internal forces (N_{top} , V_{top} , N_{bot} and V_{bot}) on the upper and lower member of the opening as described on the right of the figure 1 [3-7].

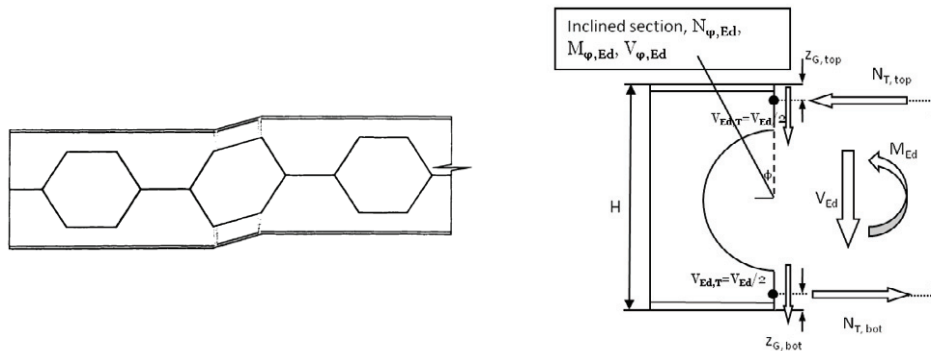


Fig. 1. Illustration of the Vierendeel mechanism (left), global and local internal forces around a circular opening of cellular beam (right)

New trends in steel construction lead to the development of new opening shapes [8]. A new type of cellular beams, called AngelinaTM beam, is made with sinusoidal shapes of openings (Fig. 2). As common cellular beams, it is made from hot rolled profiles with regular openings. Besides its aesthetic aspect, this innovative shape offers a wider range of opening sizes in comparison with circular openings. The adaptation of the analytical approach used to design standard cellular beams is given in figure 3.

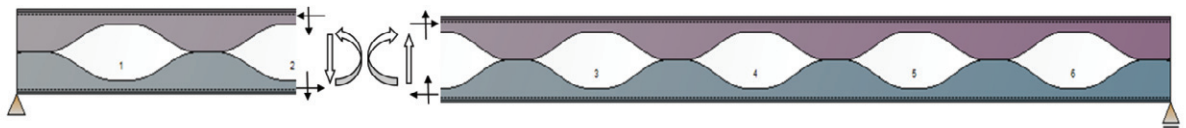


Fig. 2. Cellular beam with sinusoidal openings and local internal forces in the opening 2

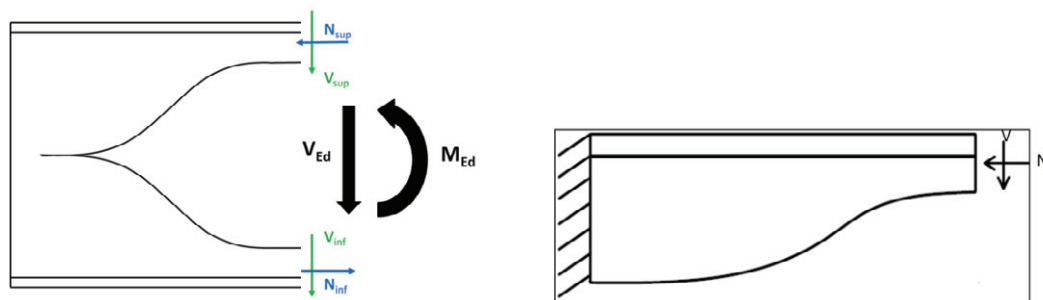


Fig. 3. Internal forces equivalent to global moment M_{Ed} and shear force V_{Ed} (left) and equivalent model of an opening quarter (right)

Changing the opening shape affects its failure mode as it was observed between hexagonal and circular openings [1]. This is also observed when new opening shapes are used [9]. Therefore, in order to characterize the behavior of cellular beams with sinusoidal openings, an experimental program is performed. The tests conducted at the University Blaise Pascal concerned three full scale beams representing various geometric

configurations (large opening, high opening and small opening). The experimental results showed the two main failure modes depending on the opening geometry: yielding of the most stressed opening or local buckling of the compressed panels. A finite element model is validated by comparison with the experimental results. This validated numerical model can be used to access to specific results which are difficult to obtain from test observations such as the stress distribution around the opening. This leads to a better understanding of the complex behavior of cellular beams.



Fig. 4. Test set-up on a full scale beam (left) and the failure of an opening from the finite element model (right)

2. Summary of numerical study

The numerical study performed for the global cellular beams with sinusoidal openings and for the isolated quarters of openings showed interesting results (both models are described in figures 2 and 3(right)). Especially it pointed out two main information:

- The opening failure can be characterized by the yielding or buckling in different parts of the opening and the global failure arises after a mechanism of failure of those different parts,
- Close stress analysis on isolated quarter of opening revealed the existence of a semi-rigid restraint between the opening member and the intermediate web-post

To do a local analysis of an opening quarter, new tests are performed on the isolated parts of cellular beams with sinusoidal openings. The test set-up is described in the figure 5. This new test campaign is used to validate the numerical model and to observe the failure modes. Shell elements taking into account geometrical and material non-linearities are used. This element is particularly efficient to represent local instability with limited resources. Previous numerical studies on cellular beams showed that the shell elements represent well the behavior of cellular beams including the local instabilities as the web-post buckling for closely spaced circular openings [7][10][11]. The model is validated on the basis of the experimental results regarding the ultimate loads and the failure modes of the specimens. The specimens are simply supported on the lower flanges and laterally maintained at the loading points to represent the lateral supports of tests. Elastic-perfectly plastic law is chosen for the material with an elastic limit taken from the measured ones. The calculation is done according to two steps. The first step concerns an Eulerian calculation to obtain the first buckling mode of the specimen. This mode is used to define the initial geometrical imperfection. The second step is a non-linear analysis with displacement control to obtain the load-displacement curve of the specimens including the descending branch that represents the post-critical range.

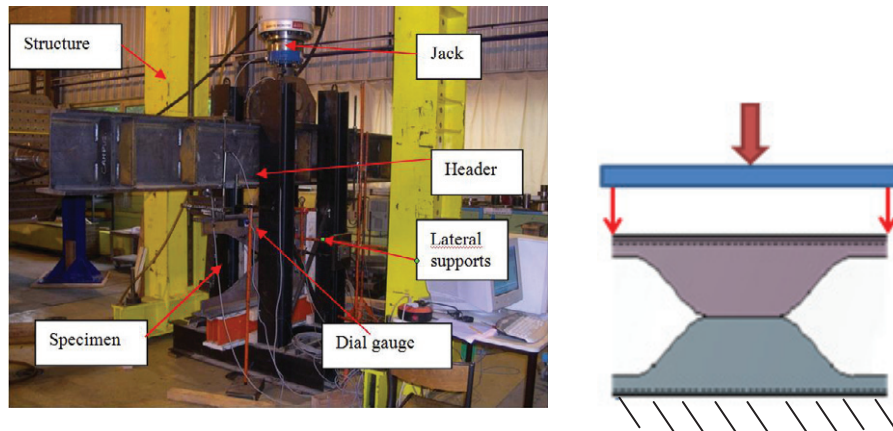


Fig. 5. Test set up (left) Opening quarter loading by shear force (right)

3. Validation of the finite element model

The figure 6 presents as example the comparison of two experimental tests (specimens B-1 and B-2) that have the same geometrical configurations of a high opening with the numerical curve with the corresponding deflected shape obtained numerically. Table 1 summarizes the results of all the tested specimens.

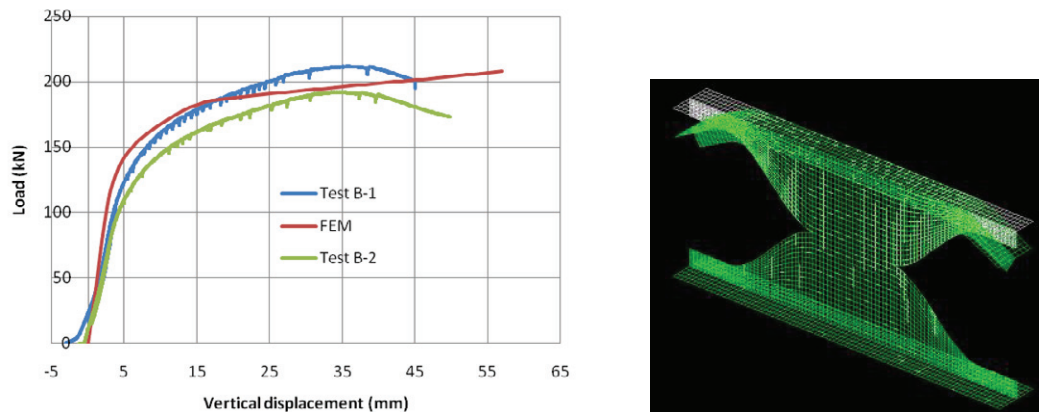


Fig. 6. Example of comparison of experimental and numerical curves (specimens B) (left) and example of numerical deflected shape (right)

Table 1. Summary of the experimental and numerical results of the tested specimens

Specimen	$F_{ult, Test}$ (kN)	$F_{ult, FEM}$ (kN)	$F_{ult, anal.}$ (kN)	FEM/Test
A-O-1	290.4	295.3	114	1.02
A-O-2	306	295.3	114	0.97
A-S-1	306.4	301.4	114	0.98
A-S-2	343.3	301.4	114	0.88
B-O-1	211.8	203.8	146	0.96
B-O-2	191.9	203.8	146	1.06
C-O-1	393.5	394.6	130	1.00
C-O-2	420	394.6	130	0.94
C-S-1	516.8	392.7	130	0.76
C-S-2	418.4	392.7	130	0.94

These comparisons (figure 6 and table 1) show the good capacity of the numerical model to represent the behavior observed experimentally. The comparison between FEM values and analytical values show that the analytical approach based on a simple adaptation of the existing models for circular openings and the Eurocode 3 design rules give too conservative results. Those comparisons show the necessity to better define the local resistance of each opening quarter before the analysis of the global mechanism of an opening.

4. Comments on the analytical model

In this simple specimen the applied load around the opening is known and represents the calculated internal load in real beams. Thus, the main reason of the differences between the analytical and the numerical ultimate loads is due to the analytical model approach defining the quarter resistance. Indeed the simple adaptation of design rules given in the Eurocode 3 [12] is not enough to predict the strength of tee section located in an opening quarter. In fact, the resistance of the panels of the tee can not be done using directly the rules for the classification of the tee sections depending only on the ratio c/t (web height over web thickness). One of the parameters to be investigated is the influence of the rotational stiffness provided by the adjacent web post on the buckling of the panel around the opening. An illustration of the results for the classification of the tee sections along the opening quarter is given on figure 7. The classes define the capacity of each section to yield before the occurrence of local buckling. Therefore, as this design rule is only based on the tee web height, the sections close to the web-post (represented by hatchings in the figure 7) are class 4 which correspond to sections that are considered to buckle before the most compressed fiber reaches its elastic limit. This can explain the fact the resistances of the panels close to the web-post are not well predicted.

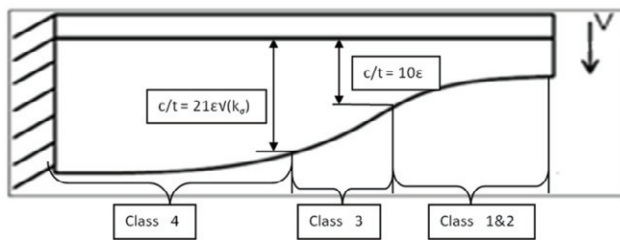


Fig.7. Adaptation of eurocode 3 design rules for the classification of the tee sections along the opening quarter submitted to simple bending

The figure 7 points out the fact that for the “long” openings the analytical model does not consider the out of plan support provided by the intermediate web-post to the adjacent tee sections and leads to conservative results. A work in progress, using the validated numerical model, is based on parametrical study aiming to define precisely the out of plan support and the possible rotational restraint provided by the intermediate web post. This restraint depends on the geometrical characteristics of a sinusoidal opening as illustrated in figure 8. This figure describes the two geometric models that will be used to calibrate the elastic restraint coefficient k_0 applied on the isolated quarter model.

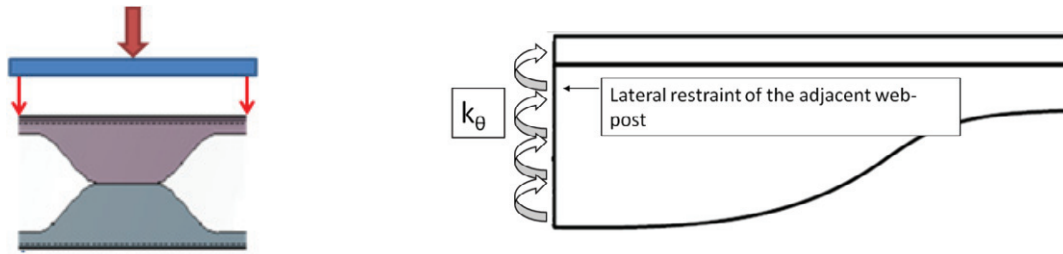


Fig. 8. Illustration of the model used to calibrate the value of elastic restraint (k_θ) provided by the web post

5. Conclusion

The various types of specimens tested showed two main failure modes, which are the yielding of the sections at the linear part of the opening and the instability in the sinusoidal panels. The first mode arose for the specimen with large opening where the dimension of the sinusoidal part is small. The failure modes of the specimens with a web-post and two quarters of openings are similar to those observed in the whole beams.

The developed numerical model represented accurately the local behavior observed on the specimens. Thus, it can be used as a tool for further parametrical studies of the local failure of the isolated part of the sinusoidal opening. This parametrical study will be based on Eulerian calculation so as to accurately estimate the stiffness of each model independently of the elastic-limit or second order effects. By comparing the first eigen mode force of a model of simple quarter with elastic restraint and the first eigen mode force of the model of the tested samples it is possible to calibrate, considering the geometrical parameters, the elastic restraint provided by the intermediate web-post to the opening quarter.

The analytical model will use the principles of Eurocode such as the sections classes but with partial restraints. It has to be validated at the final stage on the whole beams with general geometrical and material characteristics.

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